CALIBRATED PERTURBATIONAL RF FIELD STRENGTH MEASUREMENTS

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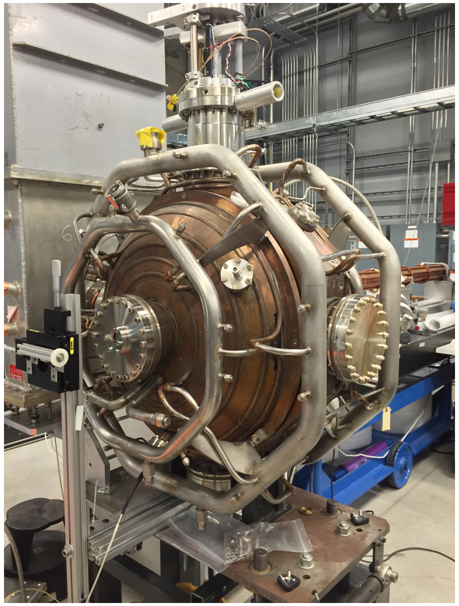
INTRODUCTION

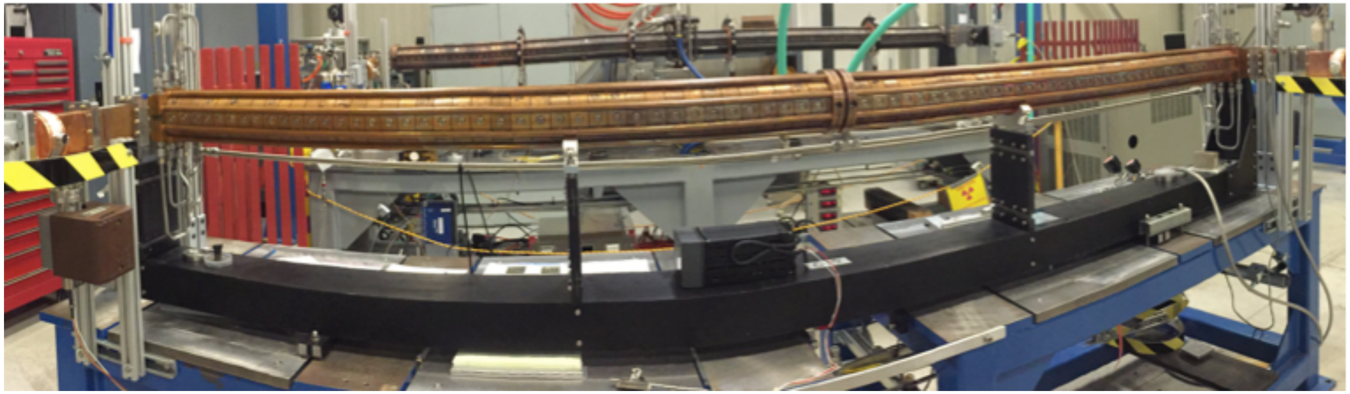
Figure of merit in RF cavities is R/Q, shunt impedance over quality factor:

$$\frac{R_s}{Q_L} = \frac{V_{acc}^2}{\omega U} = \frac{\left(\int E_z e^{j\frac{\omega}{\beta c}z} dz\right)^2}{\omega U}$$

- Calibrated perturbing objects allow for absolute measurements
- R/Q measured for different types of structures
  - Travelling wave: confirm monopole R/Q
  - Standing wave: Longitudinal higher order modes (HOMs) increase energy spread



APS Storage Ring Cavity



APS Linac Cavity

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THEORETICAL BACKGROUND

Given a cavity with resonant frequency ω_0, change in frequency due to perturbation of the cavity is given by

$$\frac{\Delta\omega}{\omega_0} = -\frac{\int_V (\Delta\epsilon \vec{E} \cdot \vec{E}_0^* + \Delta\mu \vec{H} \cdot \vec{H}_0^*) \cdot dV}{4U}$$

This can be represented by

$$\frac{\Delta\omega}{\omega_0} = \frac{1}{U}\left(F_1 E_\parallel^2 + F_2 E_\perp^2 + F_3 H_\parallel^2 + F_4 H_\perp^2\right)$$

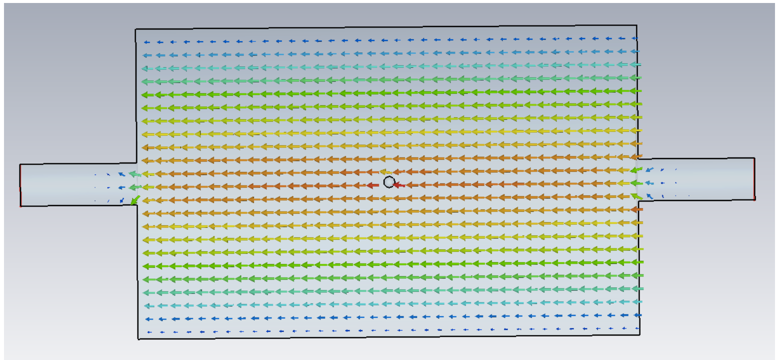
However, transmission coefficient phase shift is used for its greater accuracy

$$\frac{\Delta\omega}{\omega_0} \approx \frac{1}{2Q}\tan(\Delta\phi_{21}) \quad \rightarrow \quad \frac{R_s}{Q_L} = \frac{1}{2\pi\epsilon_0}\left(\int dz \sqrt{\frac{\tan\Delta\phi_{21}}{2Q_L}\frac{1}{F_1}}\right)^2$$

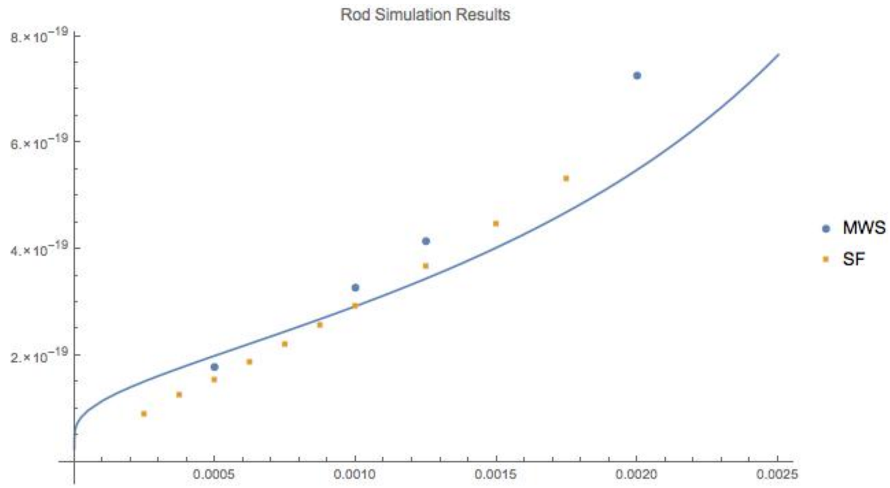
SIMULATION AND ANALYTICAL APPROXIMATIONS

- Simulations carried out in Poisson Superfish (SF) and CST Microwave Studio (MWS)
  - Superfish allowed for greater precision and accuracy
  - MWS did not have geometric limitations
- Simple geometries such as spheres do not isolate components
- Ellipsoidal approximations are done for rods and needles

$$\frac{\Delta\omega}{\omega_0} = \frac{1}{U} F_1 E_{\|}^2$$



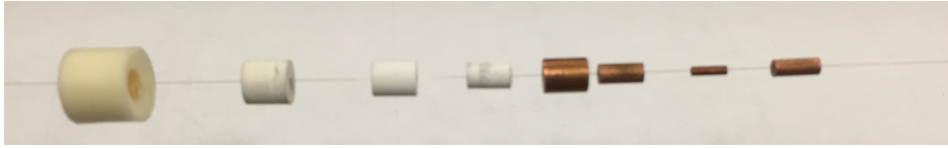
Pillbox Simulation with Sphere



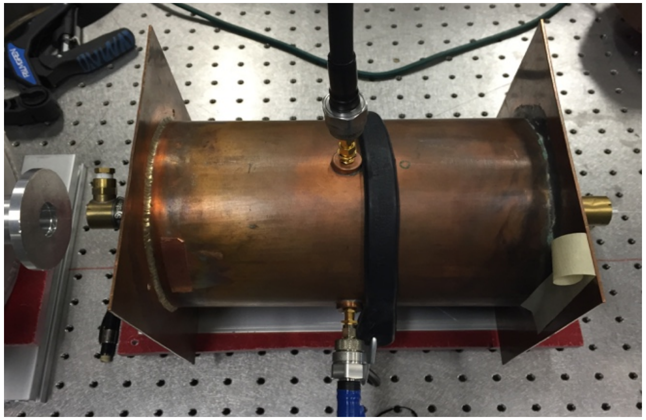
Rod Simulation Results

EXPERIMENTAL TEST CAVITIES

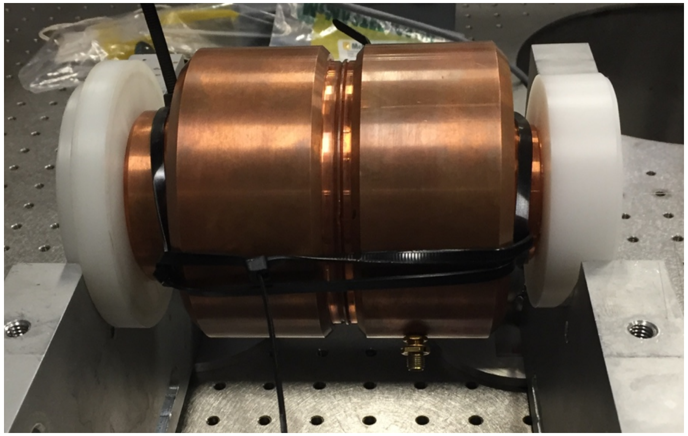
- Pillbox cavities are easily simulated to find energy and fields to calibrate beads
- L-Band and S-Band cavities used
  - L-Band: Single cell cavity, less precisely machined
  - S-Band: 2 cell cavity, lacked exact dimensions



Cylindrical beads used with length of 5 mm



1.7 GHz Pillbox

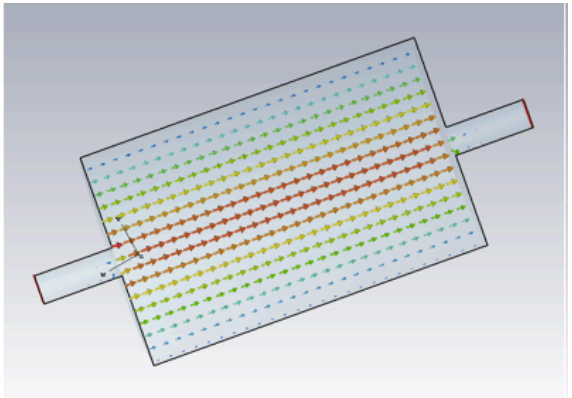


2.8 GHz Coupled-Cavity

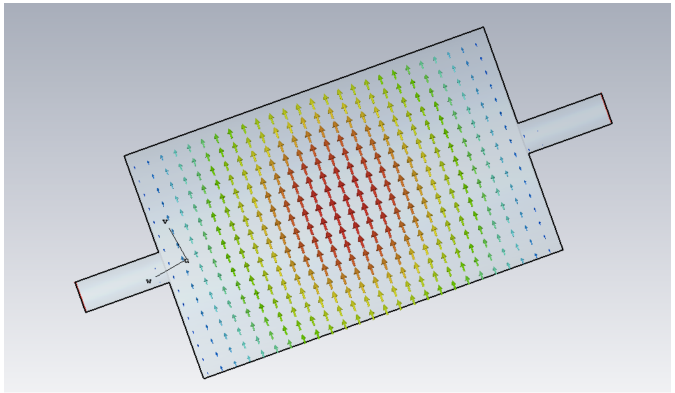
FORM FACTOR MODE SELECTION

- To measure different form factors, different field components needed to be isolated on axis

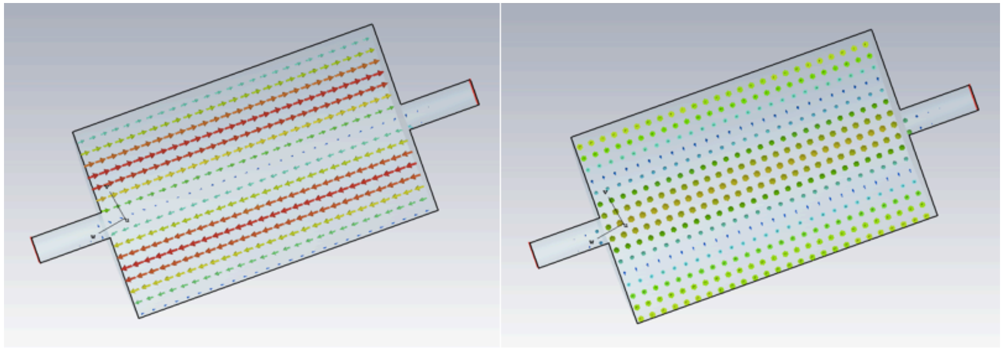
$$\frac{\Delta\omega}{\omega_0} = \frac{1}{U}\left(F_1 E_{\parallel}^2 + F_2 E_{\perp}^2 + F_3 H_{\parallel}^2 + F_4 H_{\perp}^2\right)$$



E-Field used to measure F1



E-Field used to measure F2



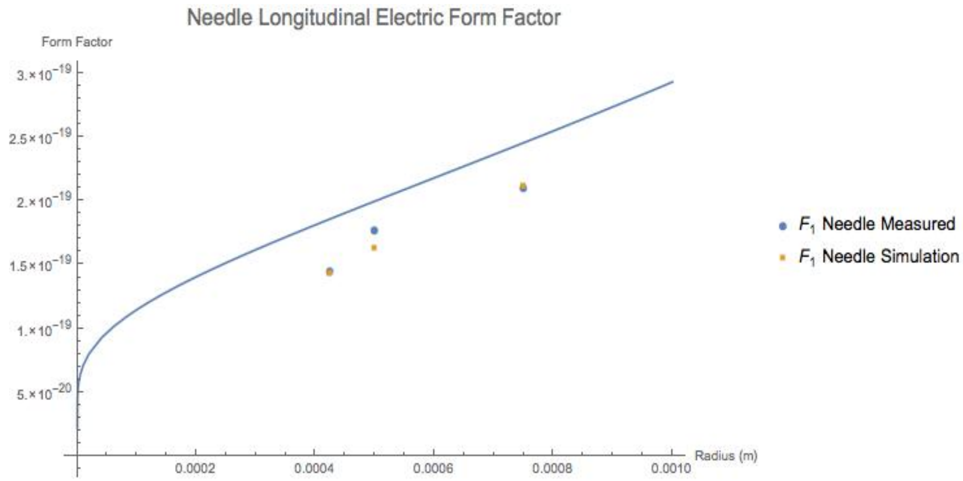
E-Field (left) and H-Field (right) to measure F4

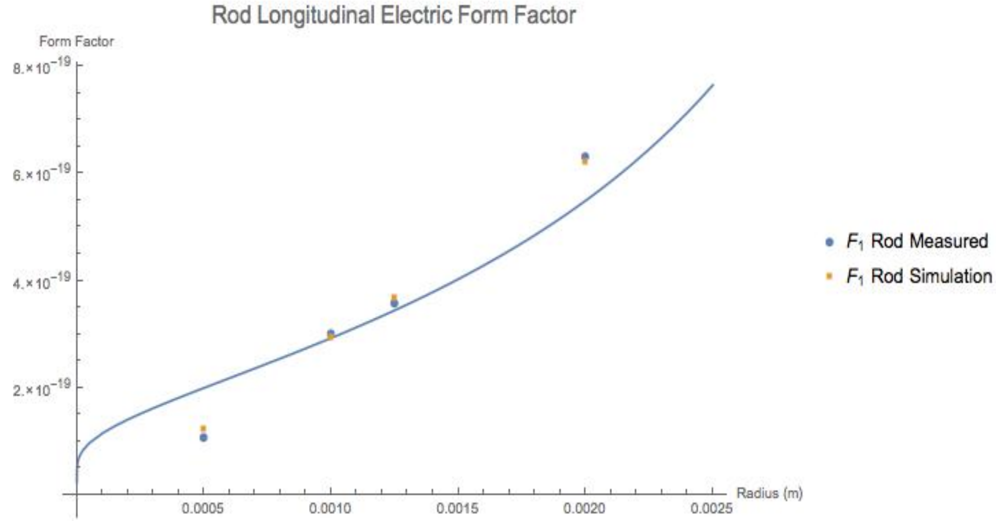
LONGITUDINAL ELECTRIC FORM FACTOR

Bead	Length (mm)	Radius (mm)
Rod 1	4	0.5
Rod 2	5	1
Rod 3	5	1.25
Rod 4	5	2
Needle 1	5	0.425
Needle 2	5	0.5
Needle 3	5	0.75
DE Rod 1	5	1.5
DE Rod 2	5	2
DE Rod 3	5	2.5
Sphere	N/A	2.35

Bead Dimensions where DE stands for Dielectric

Bead	Measured F_1	Simulated F_1	Error
Rod 1	1.079	1.20	9.78%
Rod 2	3.0123	2.90	3.70%
Rod 3	3.567	3.65	2.32%
Rod 4	6.316	6.20	1.85%
Needle 1	1.441	1.42	1.52%
Needle 2	1.768	1.63	8.77%
Needle 3	2.095	2.11	0.75%
DE 1	1.573	1.59	1.17%
DE 2	2.554	2.69	5.16%
DE 3	3.733	3.97	5.88%
Sphere	3.665	3.540	3.70%

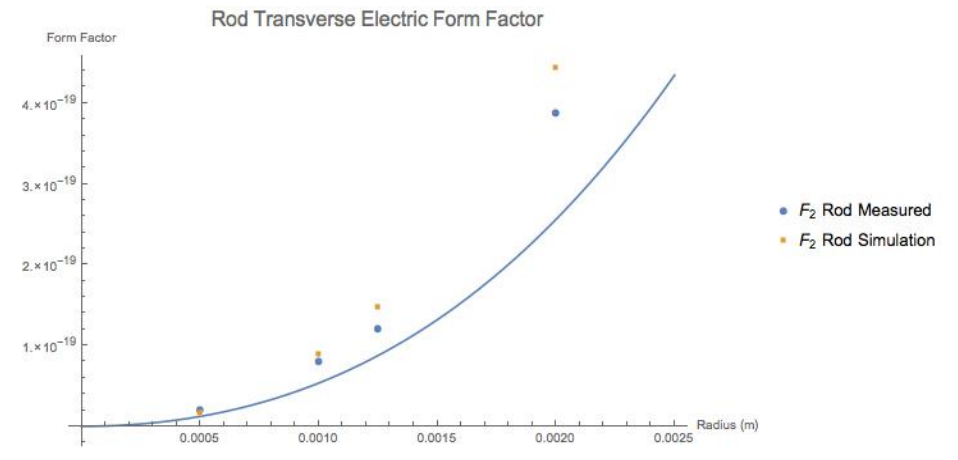


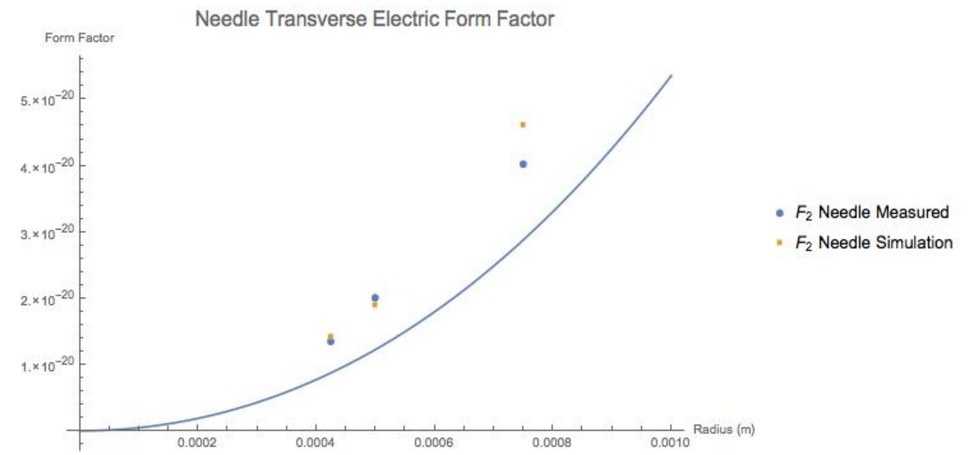


Needle (top) and Rod (bottom) F1 plotted against bead radius

TRANSVERSE ELECTRIC FORM FACTOR

Bead	Measured F_2	Simulated F_2	Error
Rod 1	0.201	0.156	28.7%
Rod 2	0.802	0.888	9.67%
Rod 3	1.204	1.468	17.9%
Rod 4	3.877	4.425	12.4%
Needle 1	0.134	0.141	4.29%
Needle 2	0.201	0.188	7.16%
Needle 3	0.402	0.459	12.4%
DE 1	1.069	1.337	20.0%
DE 2	2.006	2.472	18.9%
DE 3	3.276	4.026	18.6%
Sphere	3.475	3.659	5.02%





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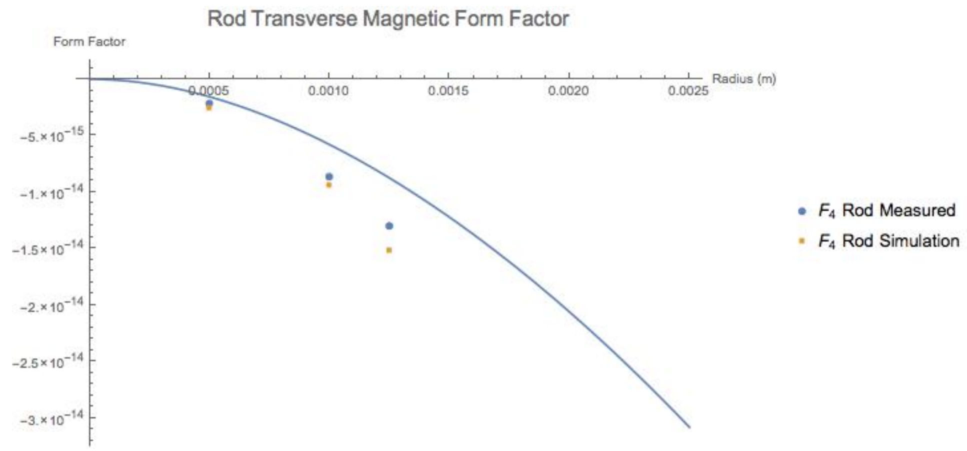
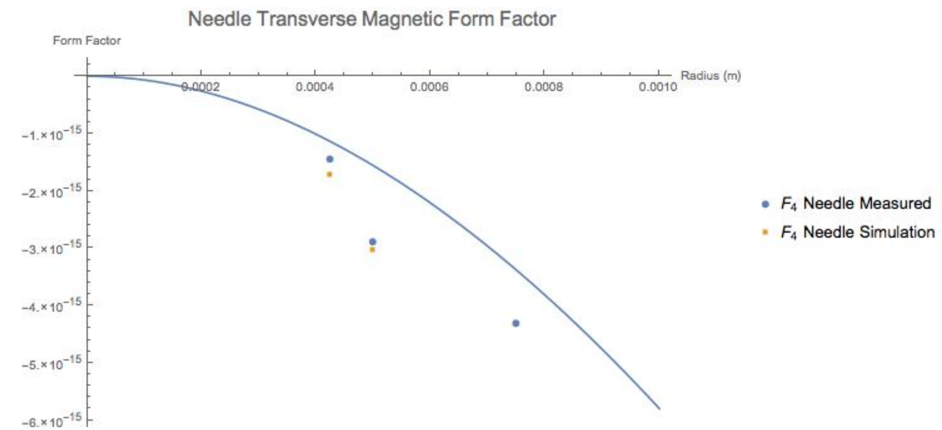
TRANSVERSE MAGNETIC FORM FACTOR

Bead	Measured F_4	Simulated F_4	Error
Rod 1	−2.193	−2.601	15.7%
Rod 2	−8.655	−9.541	9.28%
Rod 3	−12.97	−15.25	14.9%
Rod 4	−34.62	−33.97	1.90%
Needle 1	−1.454	−1.729	15.9%
Needle 2	−2.885	−3.053	5.5%
Needle 3	−4.316	−6.241	30.8%
Sphere	−25.96	−24.27	7.0%





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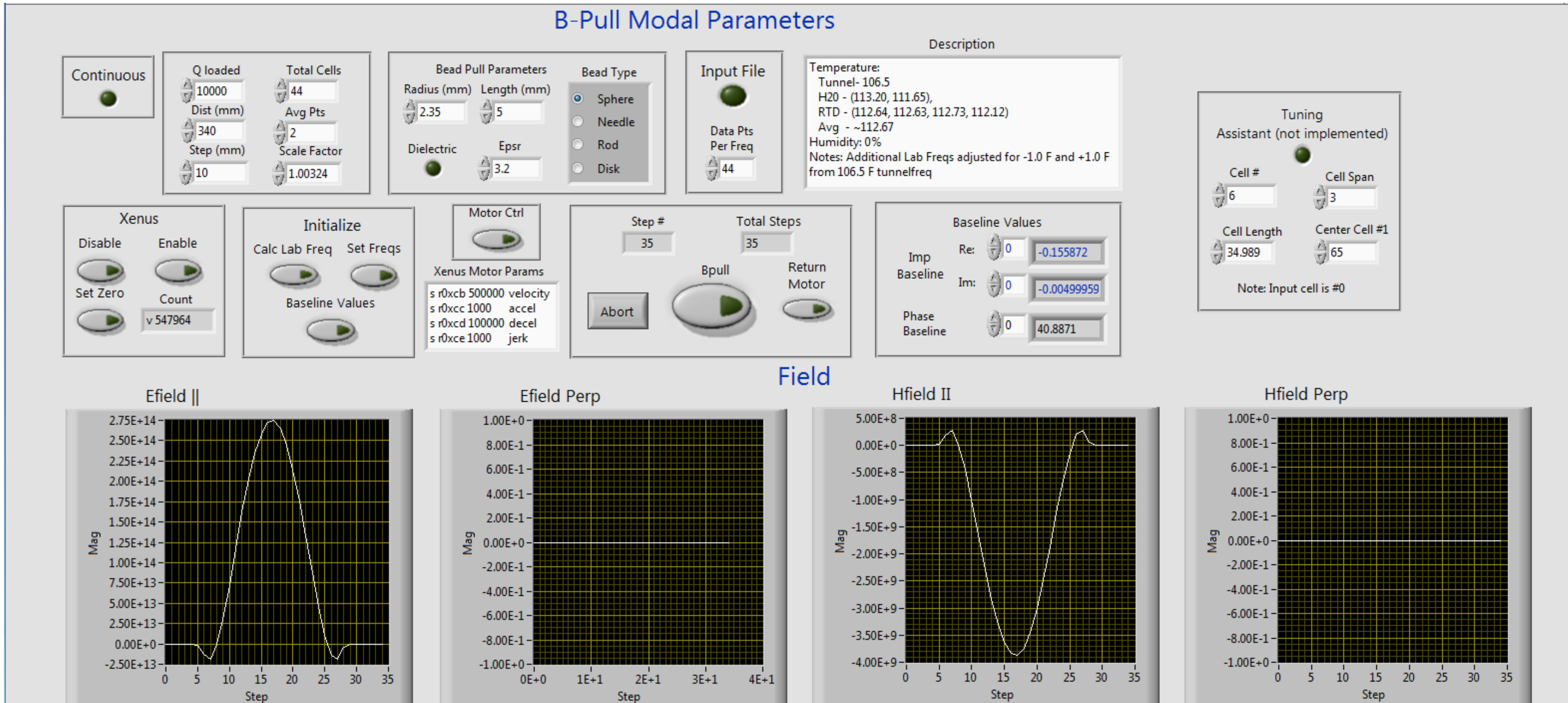
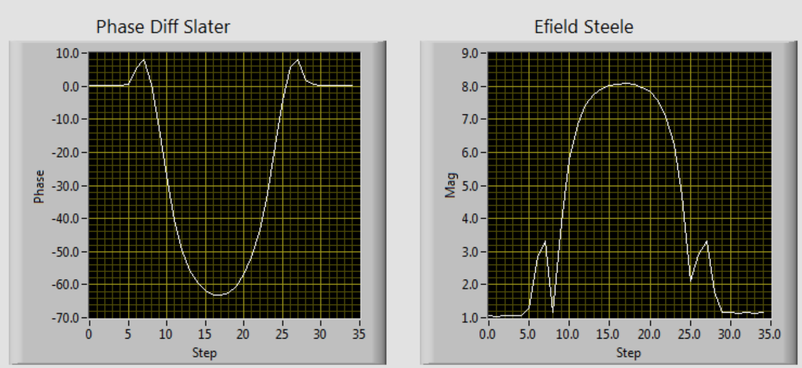
LABVIEW PROGRAM

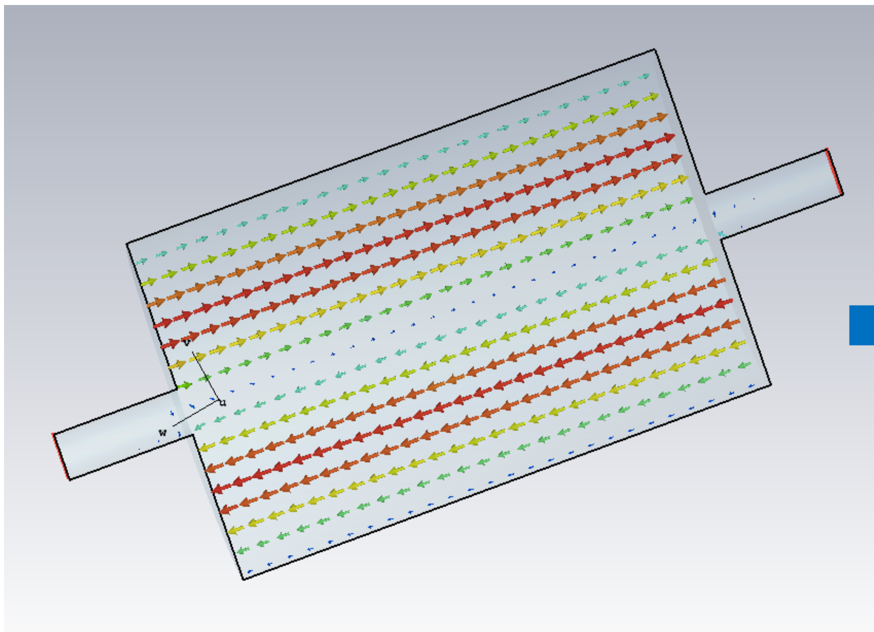


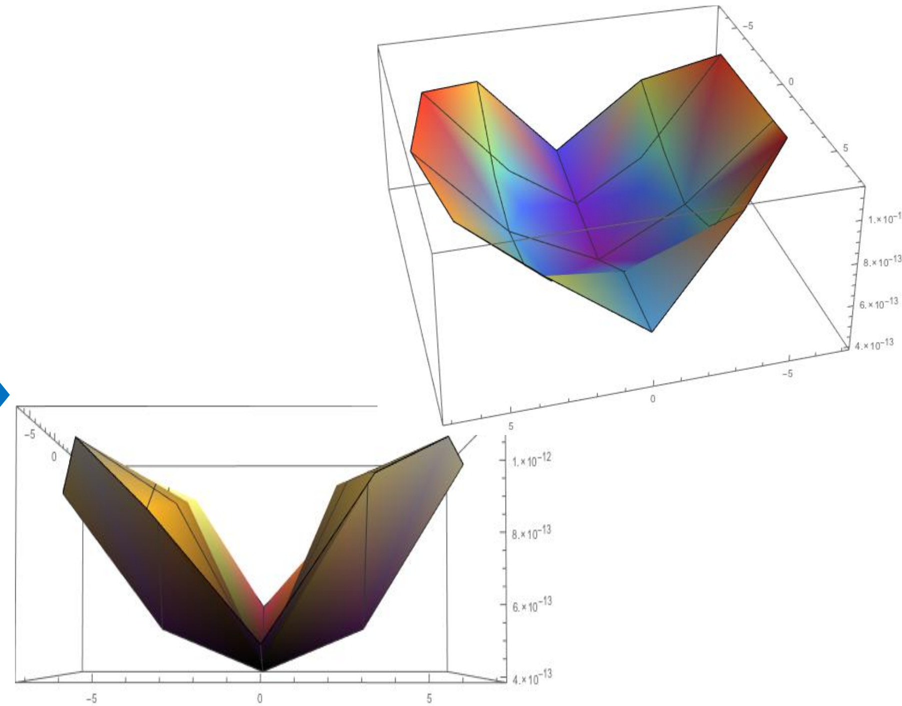


- Transmission phase data used to create field profiles
- Different beads create different profiles for the same modes
- Field profiles used to match with modes from simulation

ELECTRICAL AXES FROM DIPOLE MODE

- Dipole mode used to locate electrical center of cavity, as dipole R/Q is normalized with displacement from center





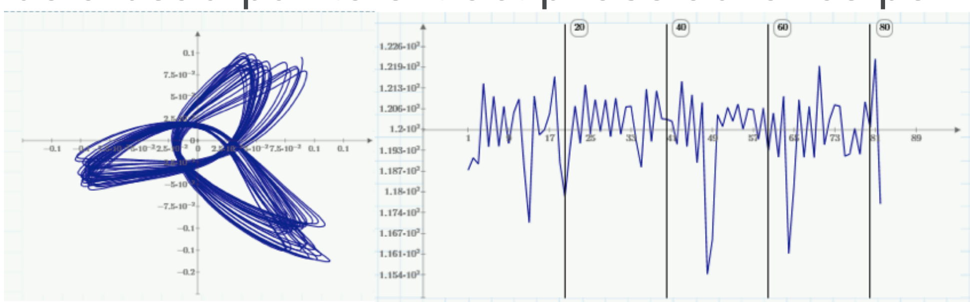
Dipole mode used to find center for accurate HOM R/Q measurements

TRAVELLING WAVE STRUCTURES

- For multiple cell cavities, phase advance must be taken into account

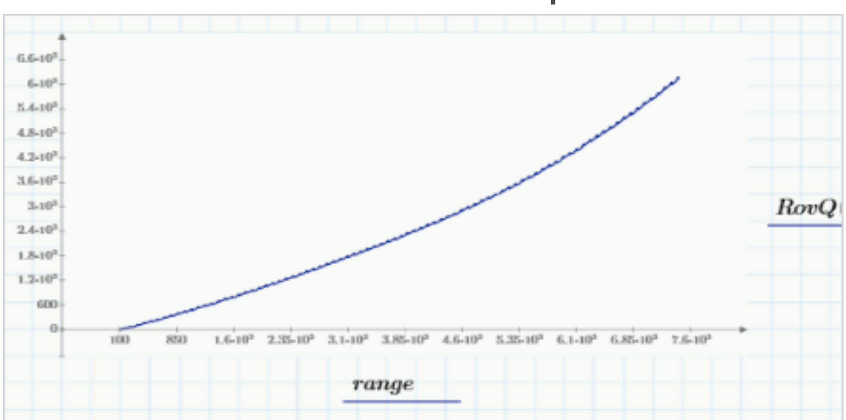
$$\frac{R}{Q} = \frac{1}{\omega U} \left| \int E_z e^{j \frac{\omega}{\beta c} z - \phi(z)} dz \right|^2$$

- First do a bead-pull to extract phase advance per cell

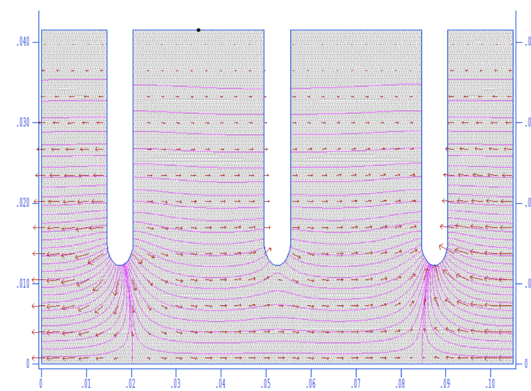


Reflection coefficient (left) and Phase Advance vs. Cell (right)

- Combine this with transmission phase for R/Q



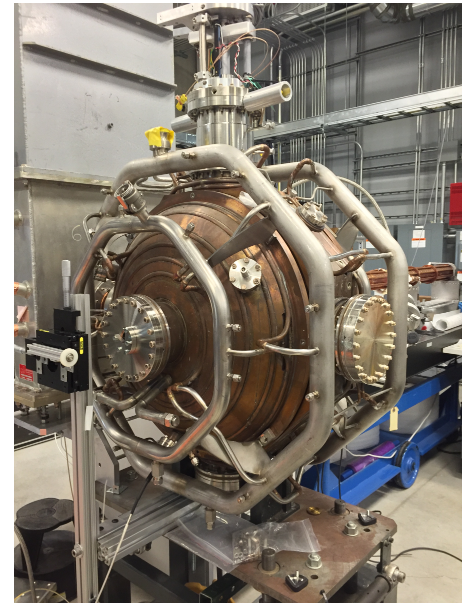
R/Q progresses uniformly from cell to cell once phase advance is taken into account

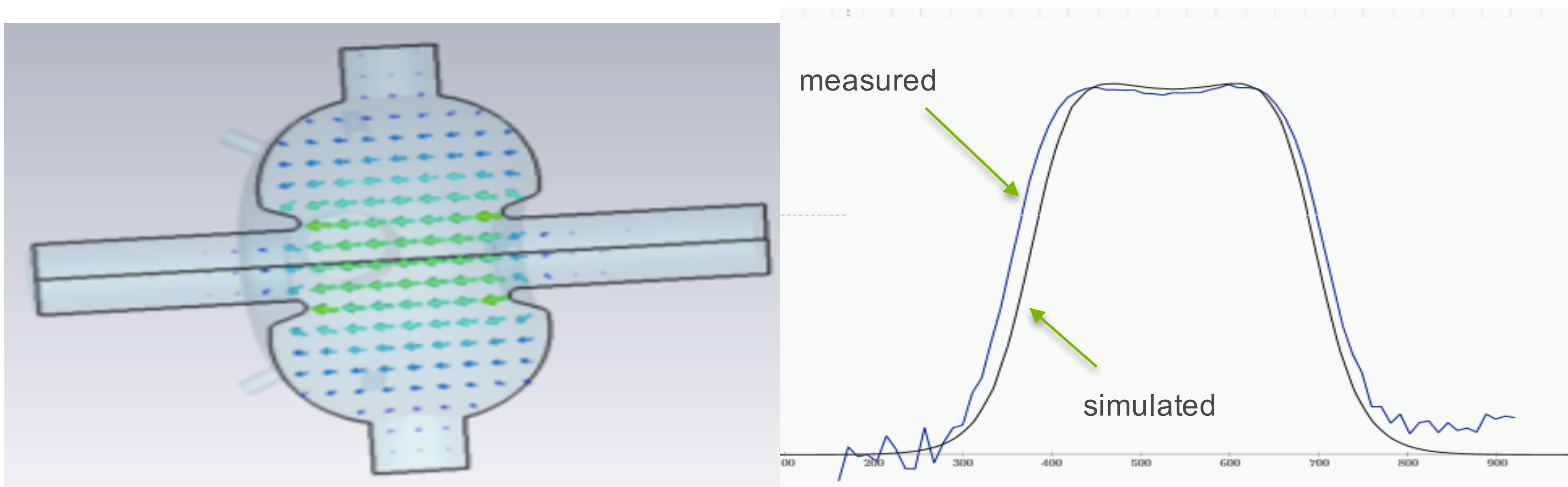


SF Simulation showing phase advance

STANDING WAVE STRUCTURES

- HOMs in Storage Ring (SR) cavities cause instabilities
- TE HOMs cause beam blow-up and eventual beam loss
- Longitudinal HOMs cause energy spread in beam and are of particular interest for MBA
- Our bead-pulls determine which HOMs are problematic

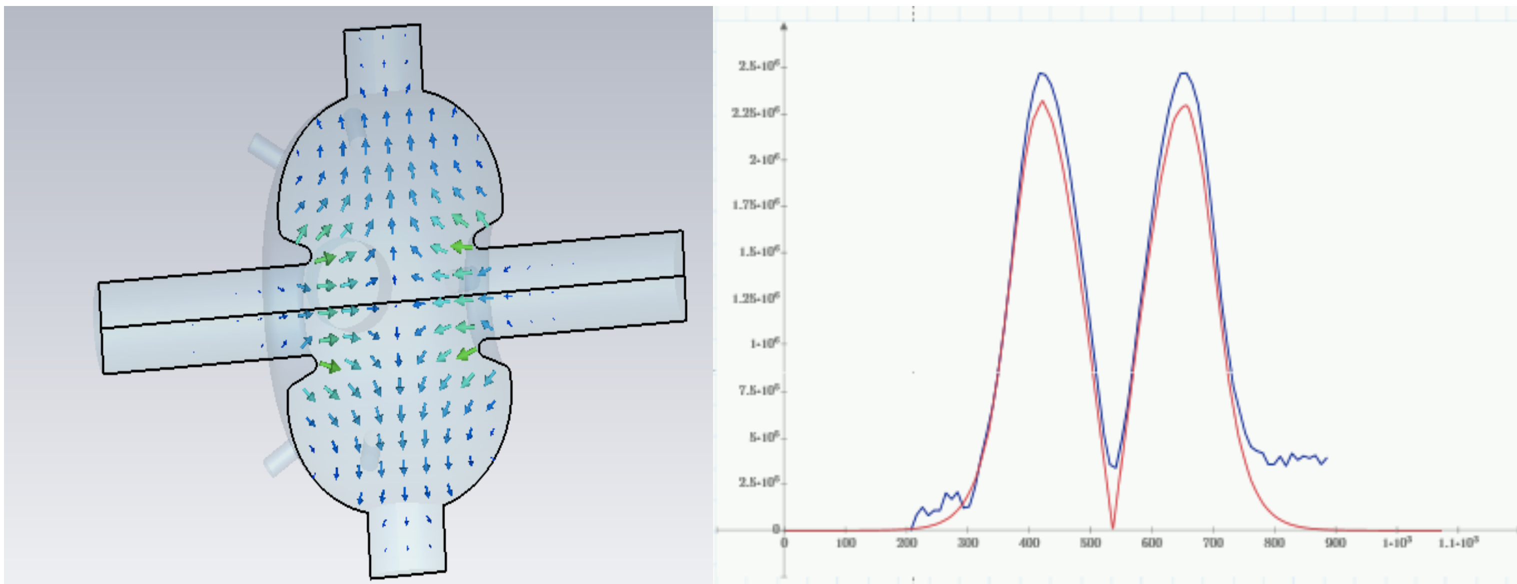




Monopole mode in SR Cavity

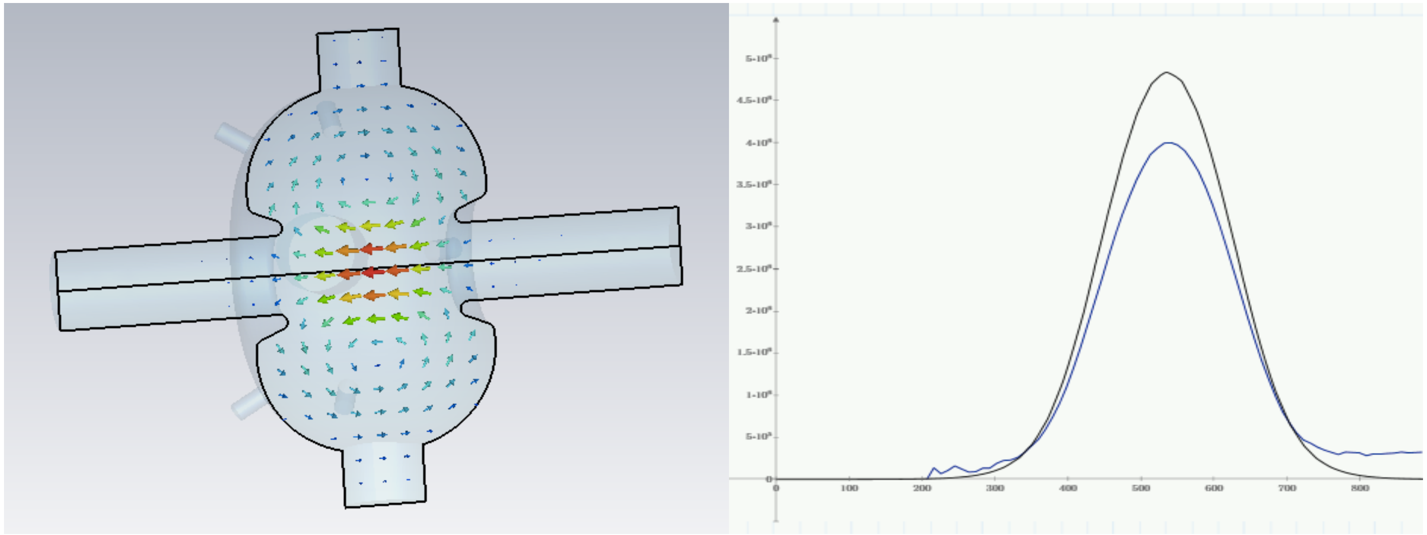
HOM CLASSIFICATION

Frequency (MHz)	Measured	Simulated	Error
352	225.3	226.4	0.5%
535	100	81.8	22.2%
916	8.66	9.1	4.8%
938	8.36	6.6	26.7%

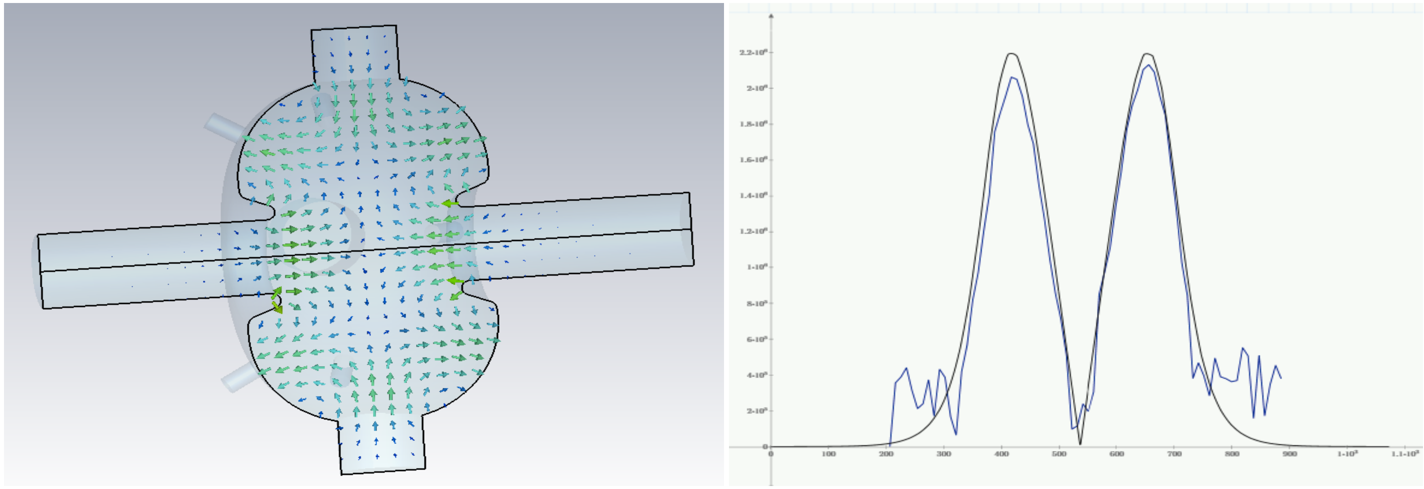


HOM at 535 MHz with measured and simulated data

HOM CLASSIFICATION (CONT'D)



HOM at 916 MHz



HOM at 938 MHz

FUTURE PLANS

- Find better way to couple to HOMs

- Extend methodology to be able to analyze other scattering matrix elements

$$\phi_{21} \approx \arctan\left(\frac{\Im(S_{11})}{1 + \Re(S_{11})}\right) \qquad |E_z(\vec{r})| = \alpha \cdot \sqrt{|S_{11}(\vec{r})|}$$

- Compare test SR cavity to other SR cavity resonances to see identify problematic longitudinal HOMs

QUESTIONS?

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REFERENCES

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[6] H. Wang and J Guo *Bead-pulling Measurement Principle and Technique Used for the SRF Cavities at JLab.* USPAS 2015.